

## DC ELECTRICAL ACCELERATED AGEING TESTS ON POLYETHYLENE INSULATION

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### INTRODUCTION

Accelerated short term ageing tests conducted on polyethylene are commonly used as a means of estimating the long term performance and reliability, (as required under service conditions), of the bulk insulation. Several models have been proposed for estimating and describing the performance of insulating materials, Cygan and Laghari (1), and Stone and Lawless (2).

The above models propose that the lifetime expectancy of polyethylene as a function of applied dc stress obeys a generic power law relationship.

$$T = KE_{app}^{-m} \quad (1)$$

where  $T$  is the time to failure, (usually the Weibull scale parameter), and  $E_{app}$  is the applied electric stress.

Under dc conditions the electric stress distribution can be time dependent, due to the build up of space charge in the bulk. The distinction between applied stress, ( $E_{app}$ ), and effective stress, ( $E_{eff}$ ), can therefore be of importance when assessing the long term ageing performance of insulating materials.

The effective stress, mentioned above, is comprised of two components, the applied stress, and the contribution from space charge formation, (which is electric stress dependent). The generation, nature, transportation, trapping, distribution, and time dependence of space charge within a dielectric material are also dependent on microscopic and macroscopic structural features in the bulk material. Chen et al (3), Bishop et al (4), have reported a correlation between microscopic structural features, (e.g. crystalline content, morphology and molecular weight), and electrical breakdown strength, or space charge accumulation.

The introduction of macroscopic structural features (amalgamation lines, particulates etc.) into the bulk material is known to reduce the insulation properties. Though no systematic study of this has been reported, Chen et al (5, 6), has studied the dc electrical breakdown strengths of polyethylenes containing particulates, and on space charge distributions in multi-layered PE/PE and PE/EVA structures.

This paper reports on an on-going study into assessing the long term dc performance and reliability of moulded production joints used in submarine repeatered optic communication cable systems. Emphasis is being placed on using meaningful short term accelerated ageing tests, results of which can be extrapolated to service life and conditions. Electrical breakdown data from ramp and constant stress tests of production mouldings are presented along with thin film samples microtomed from various parts of mouldings. Bulk space charge measurements of aged samples are reported and their effect on failure data are discussed.

### STATISTICAL FAILURE ANALYSIS

The production of dc powered cable systems requires the joining together of lengths of cable insulation, which is achieved using an injection moulding technique (with the inevitable consequence of introducing macroscopic structural features). DC high voltage testing (either progressive or constant stress), until electrical breakdown occurs, of a series of these joints should produce a distribution of results consistent with a two parameter Weibull distribution, (i.e. constant stress tests should conform to equation (2))

$$Pr = 1 - \exp[-(t/t_c)^a] \quad (2)$$

where,

$Pr$  = cumulative probability of failure.

$a$  = time exponent, (Weibull shape parameter)

$t_c$  = characteristic time to failure at a given stress, for a series of samples, (Weibull scale parameter)

Equation (3), is analogous for a progressive stress test distribution,

$$Pr = 1 - \exp[-(E/E_c)^\beta] \quad (3)$$

where,  $\beta = a + b$  and " $m$ " =  $b/a$

Note: equation (3) is expressed in terms of applied stress.

The two parameter Weibull distribution is a special case of the more general three parameter distribution, given by

$$P_f = 1 - \exp[-(\{t-\gamma\}/t_c)^a] \quad (4)$$

where  $\gamma$  = time threshold value (location parameter).

### SAMPLE PREPARATION

**Joint.** The mechanical components of the joint were assembled. Two preformed end caps were positioned over the cylindrical metallic housing and the insulation was then completed with three injection moulding processes that operated concurrently. The first moulding process joined the two end caps together over the joint major diameter. The remaining two moulding processes bonded the end caps to the cable.

**Space Charge Measurement.** The polyethylene was removed from the metal components of the joint and thin films were microtomed circumferentially from the outer surface. Samples were taken from three regions of the joint moulding, the centre mould injection port, centre mould vent port, and cable amalgamation vent port. The samples (350 $\mu$ m. thick), were then sputter coated with gold to form electrodes, to allow for the application of an electric stress, and a target on one side.

**Thin Film Electrical Tests.** The samples were microtomed from the joint using the same method as that described above, except the film thickness was between 150 and 200 $\mu$ m., gold electrodes were then sputter coated on to the samples.

### EXPERIMENTAL PROCEDURES

**High Voltage Test for Complete Joint Mouldings.** Nineteen joints were electrically stressed at a constant voltage of 150kV, and the times of failure recorded. Fourteen joints were subjected to progressive stress tests, (negative polarity), with the voltage applied at a ramp rate of 60kV min.<sup>-1</sup>, until breakdown occurred.

**Space Charge Measurement for Thin Film Samples.** The space charge in the thin film samples was measured using a Laser Induced Pressure Pulse method. In this technique, described by Laurenceau et al (7), the impact of a laser pulse on a target electrode is used to produce an intense short-duration pressure pulse which propagates through the sample at the velocity of sound. Under the effect of the mechanical disturbance, the atomic structure of the sample is compressed and two effects are observed:-

1) any charge attached to the atomic structure of the sample is displaced.

2) the relative permittivity of the sample is modified owing to the local variation in dipole and charge concentrations.

These two effects create a variation in the induced charges on the sample electrodes, which produces a short-circuit current in an external circuit. The evolution of the current,  $i(t)$ , as the pressure wave propagates through the sample is proportional to the space charge density within the sample.

A dc electric stress, (45kV/mm.) was applied to the samples, and measurements were taken periodically, for the duration of the test.

**High Voltage Test for Thin Film Samples.** Twelve samples from a region of a joint moulding were subjected to the high voltage test. Each sample was placed inside a test cell, (with one of the electrodes at earth potential), and the voltage applied until electrical breakdown occurred. The results were analysed using equation (3), and the characteristic stress and Weibull shape parameter estimated.

### RESULTS

#### High Voltage Tests for Joint Mouldings.

The constant stress test results, (Figure 1), conformed to a three parameter Weibull distribution, as described by equation (4). Using the three parameter distribution the characteristic time " $t_c$ " was estimated at 665 hours, the shape parameter, " $a$ ", at 0.6, and the time threshold value, " $\gamma$ ", at 140 hours.

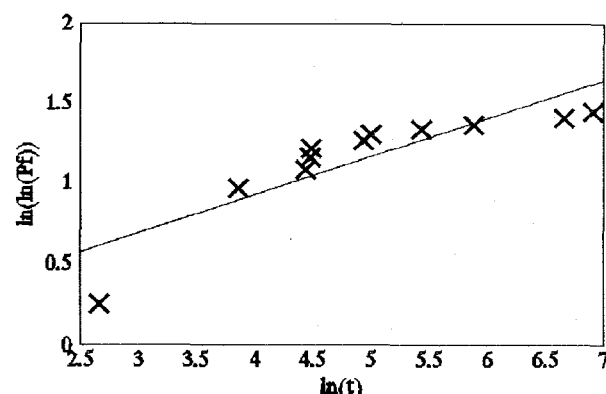


Figure 1: High voltage constant stress test results. (time in hours)

Note: When analysing the above data, only failure times associated with breakdowns on the cable amalgamation were included. All other points within the distribution were censored, as a consequence of the non uniform applied stress, and the statistical nature of the breakdown locations.

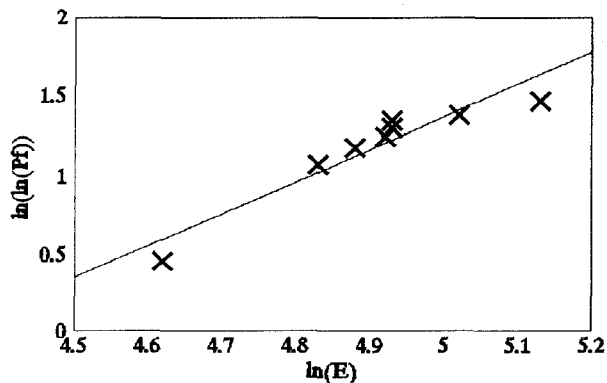


Figure 2: High voltage progressive stress test results. (electrical stress in  $\text{kV} \cdot \text{mm}^{-1}$ ).

The results, (Figure 2), from the progressive stress tests on the complete joint mouldings conformed to a two parameter Weibull distribution, described by equation (3). The characteristic breakdown stress for the cable amalgamation of complete joint mouldings was estimated at  $158 \text{ kV/mm}$ , with a Weibull shape parameter, " $\beta$ " of 6.8.

#### Space Charge Measurement for Thin Film Samples.

**Cable Amalgamation.** The thin film sample was subjected to a constant electric stress of  $45 \text{ kV} \cdot \text{mm}^{-1}$  for 350 hours. Generation of heterocharge at the electrode / polymer interface of the cathode was dominant, although some positive charge was present at the anode. Figure 3, shows the charge density, measured at intervals of time, as a result of the heterocharge formation at the cathode. Over the initial 100 hours very little charge accumulation occurred. However, after 350 hours the charge density was  $3.5 \mu\text{C} \cdot \text{cm}^{-3}$  and still increasing.

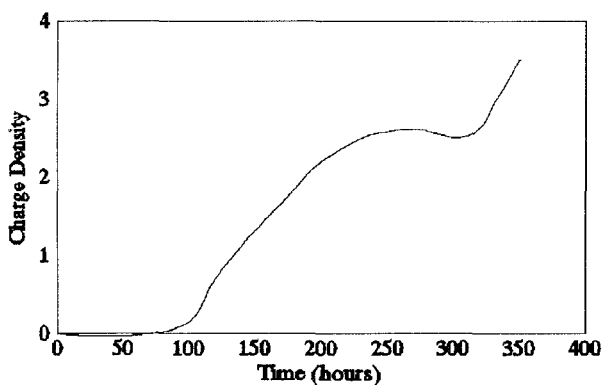


Figure 3: Heterocharge accumulation at the cathode for cable amalgamation. (charge density in  $\mu\text{C} \cdot \text{cm}^{-3}$ ).

**Centre Mould Injection Port.** The sample was subjected to a dc stress of  $45 \text{ kV/mm}$  for 432 hours. As with the cable amalgamation, generation of heterocharge at the cathode was the dominant feature. Similarly no significant space charge accumulation was detected for the first 140 hours of stress. The accumulated space charge density was significantly less

than that measured for the cable amalgamation, over a similar period of time.

**Centre Mould Venting Port.** the sample was subjected to a dc stress of  $45 \text{ kV/mm}$  for 504 hours. As with the cable amalgamation, and the centre ring injection port, generation of heterocharge at the cathode was observed. In addition a small amount of heterocharge at the anode was also measured. The charge density as a function of time is shown in figure 4.

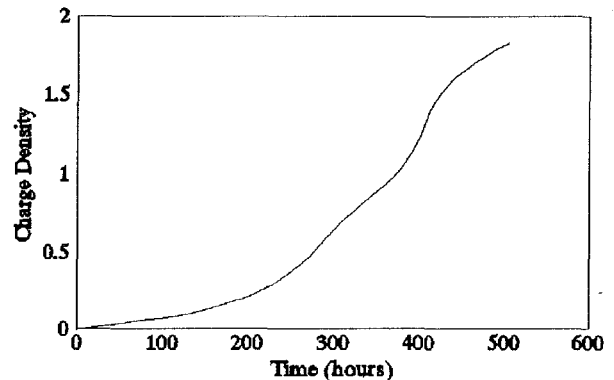


Figure 4: Heterocharge accumulation at the cathode for the centre mould venting port. (charge density in  $\mu\text{C} \cdot \text{cm}^{-3}$ ).

**Space Charge Measurement on Control Sample Plaque.** The sample was subjected to a dc stress of  $45 \text{ kV} \cdot \text{mm}^{-1}$  for a period of 432 hours. Only positive charge was measured in the sample, and was of a lower density than measured in other samples, (the maximum charge density was  $0.107 \mu\text{C} \cdot \text{cm}^{-3}$ ), with charge only accumulating after 168 hours.

#### High Voltage Tests for Thin Film Samples.

Thin film samples were prepared and tested as detailed, with the results, in Table 1, being analysed utilising equation (3). As expected the characteristic breakdown stresses were considerably higher than those for the complete joint moulding.

The control samples were compression moulded directly from the granules. The conditions used for the compression moulding were comparable with those used during the injection moulding process of the joint.

TABLE 1 - High Voltage Performance of Thin Film Samples.

	$E_c / (\text{kV/mm})$	$\beta$
Cable Amalgamation	340	6.7
Centre Mould Vent Port	357	4.8
Control Samples	430	11.5

## DISCUSSION

Although the applied stress on the film from the cable amalgamation, for the space charge measurements, was lower than that applied during the constant stress test on the joint mouldings, results did confirm the evidence of a time threshold for space charge accumulation in the cable amalgamation, (see figure 3). Whilst the applied stress will affect the time threshold value, results from figures 3 & 4 indicated that the processing conditions of the polyethylene predominantly determines any threshold value, (within the range of electrical stresses studied).

The applied breakdown strength of the samples microtomed from the joint, were considerably lower than those obtained from the control samples. The differing morphological and structural features in these samples may act as charge trapping sites, which result in local stress enhancement.

The form of the distributions, for the progressive and constant stress tests can be explained by differing space charge mobilities within the samples. Zhang et al (8), has proposed that highly mobile space charge does exist within a bulk sample. This highly mobile space charge cannot be measured using the Pressure Wave Propagation (PWP) method, due to the fast charge decay rate. Progressive stress tests of short duration (minutes), will predominantly generate highly mobile space charge within the sample, and it is this charge, (not the less mobile space charge), which is responsible for any electrical stress enhancement, resulting in electrical breakdown.

## CONCLUSION

The mechanism of electrical breakdown of LLDPE under dc conditions is dependent on the duration of the test. Over short term, (minutes), high voltage breakdowns result from electric stress enhancement caused by highly mobile space charge within the sample. Over long term, (weeks), high voltage breakdowns result from electrical stress enhancement caused by low mobility space charge. The longer term electrical breakdown tests conform to a three parameter Weibull distribution, (distinct from the short term electrical breakdown tests which conform to a two parameter Weibull), with a threshold time predominantly dependent on the processing conditions of the polyethylene.

Extrapolation of test results from short term constant stress tests, or progressive stress tests, will lead to an inaccurate estimation of the life expectancy of the polyethylene insulation. Tests used to estimate life time expectancy should therefore be of sufficient duration and stress to allow the low mobility space charge

density to reach saturation. Use of the power law relationship, equation 1, is then valid once " $E_{eff}$ " reaches a constant value, and is no longer time dependent.

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